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14. ABSTRACT

The generation of plasmadynamic discharges for near surface aerodynamic application holds the promise of providing rapid and flexible steering control for advanced high speed flight vehicles. Effective manipulation of a flow field using flow control technologies can lead to a maneuverability, payload and range, as well as lowered cost. The John Hopkins University Applied Physics Laboratory is investigating the time dependent fluid dynamic interactions between collocated pulsed jets in order to demonstrate a potentially revolutionary system for high speed flow control that leverages spark jet technology.

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ENERGETIC FLOW CONTROL

AFOSR GRANT NUMBER FA9550-07-1-0163

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Abstract
The generation of plasmadynamic discharges for near-surface aerodynamic applications holds the promise of providing rapid and flexible steering control for advanced high-speed flight vehicles. Effective manipulation of a flow field using flow control technologies can lead to a number of significant benefits to aerospace vehicle systems, including enhanced performance, maneuverability, payload and range, as well as lowered overall cost. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is investigating the time-dependent fluid dynamic interactions between collocated pulsed jets in order to demonstrate a potentially revolutionary system for high-speed flow control that leverages SparkJet technology. The plasmadynamic SparkJet actuator generates exhaust streams that penetrate supersonic as well as subsonic boundary layers. Practical application of the actuator technology will require the development of an array of individually programmable plasmadynamic actuators. Under AFOSR sponsorship, both computational and experimental techniques are being used to investigate the fundamental operating modes of a prototype actuator array. Once pulsed jet phasing and potential amplification effects are fundamentally understood, a lumped parameter model will be developed and used to optimize the array of individually programmable plasmadynamic actuators for normal force generation.

Motivation
Active flow control research has seen a resurgence over the last decade due to potential gains in performance in a number of areas, such as in external aerodynamics, internal flows through propulsion systems, noise control and other flow control applications. For flow control to become practical, there is a need for developing effective actuators that can be adapted for specific applications.

Although successful at low speeds, most actuators to-date are not very effective when the flow velocities are large compared to the typical perturbation velocities produced by the actuator. This is primarily because the magnitude of the actuator output becomes relatively small with respect to the inertia of the mean flow. Some advances have been made recently in designing actuators with higher amplitude output. Although they show some promise, the complexity of the designs needs to be simplified for use on realistic platforms. In addition to high-amplitude outputs, there is also a need for actuators with a large dynamic range where the actuation frequency can be varied to take advantage of the inherent instabilities/time-scales in the base flow (that is being controlled).

Background

The SparkJet is a completely solid-state device that consists of a small chamber with electrodes and a discharge orifice. High chamber pressure is generated by rapidly heating the gas inside the SparkJet using an electrical discharge. The pressure is relieved by exhausting the heated air via an orifice. A single cycle of SparkJet operation (Figure 1) consists of three distinct stages:[1] energy deposition, discharge, and recovery. The device transfers momentum to the external surroundings without net mass transfer.

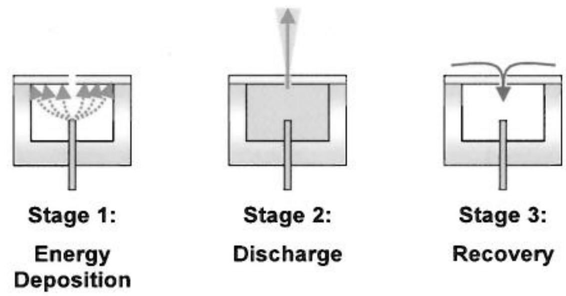

Figure 1: SparkJet operating cycle.

The global characteristics of a single discharge cycle have been studied under a JHU/APL Independent Research and Development seedling and a previous AFOSR research grant (FA9550-04-1-0095, SparkJet Actuators for Flow Control). For completeness, a brief description of these activities now follows.

Computational Studies

Both 2D and 3D time-dependent Navier-Stokes calculations of the SparkJet operation have been conducted. A parametric study was conducted to quantify the sensitivities of single-pulse device performance to orifice diameter, D_{ex}, chamber volume, V_{ch}, and energy deposited, Q, for the SparkJet firing into quiescent air (E is the internal energy). The effects of increasing Q on total impulse are shown Figure 2. Based on these results, a SparkJet can be calibrated for a specific application by varying the energy deposition and orifice diameter. Computational results shown in Figure 3 indicate that a single discharge is sufficient to penetrate supersonic boundary layers. SparkJet operation in synthetic jet mode (target frequencies up to 1 KHz) significantly increases the effect of the effluent on the surroundings.

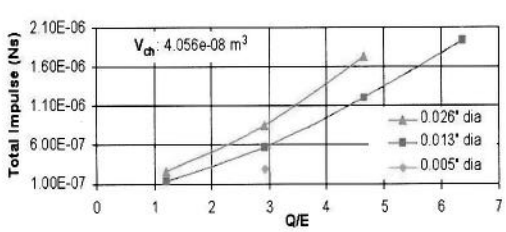

Figure 2: Effect of energy deposition on impulse.

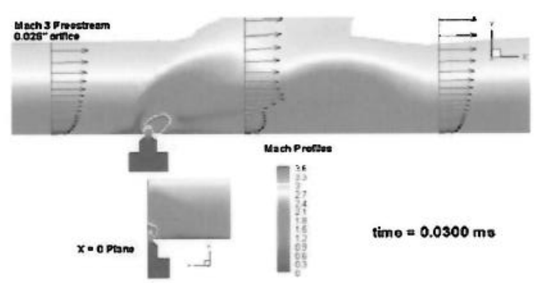

Figure 3: CFD simulation of a SparkJet pulse penetrating a Mach 3 boundary layer.

PIV Flow Field Measurements

Detailed experimental analyses of the SparkJet flow characteristics were explored using advanced flow visualization techniques. Device operation was examined using high-resolution particle image velocimetry (PIV) at The Laboratory for Experimental Fluid Dynamics at the Johns Hopkins University (JHU).[2] The SparkJet device is mounted inside an acrylic test

chamber that is mounted on an optical frame and is seeded with smoke particles (1-3 μm in diameter). The internal chamber of the SparkJet device is not seeded with particles. The SparkJet power supply, laser and camera controllers, and the data acquisition system are all synchronized.

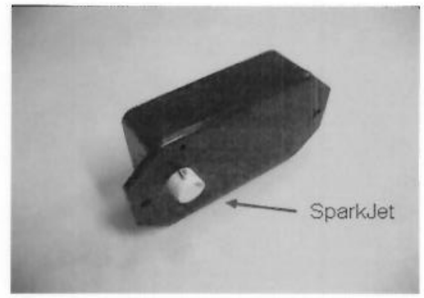

Figure 4: Individual SparkJet unit (with electronics, power supply).

Triggering requirements for high-resolution PIV studies necessitated a redesign of the original two-electrode SparkJet design. The result was a three-electrode configuration that reduced the size of the power supply, allows easy synchronization, and increased reproducibility and reliability (Figure 4). The ability to control the timing and synchronization of the discharge is inherent in this design, allowing measurements to be timed precisely with device operation.

The actuator device used in the PIV studies[3] had an orifice diameter of D_{ex}=0.33mm (0.013 inches) and a chamber volume V_{ch}=4.228E-8m^3. This SparkJet was operated at 0.2 Hz to examine the characteristics of a single pulse. Figure 5 shows the resolved velocity fields at two different timing phases as well as the vorticity components calculated using finite differencing. Visible in the velocity field snapshot at t=25 μs is the wave front propagation when the air at the puff interface is significantly compressed. At t=200 μs, the measured velocity of the entrained fluid reaches a peak value of 100 m/s. The actual speed at the jet core is believed to be much higher due to insufficient seeding in the core area.

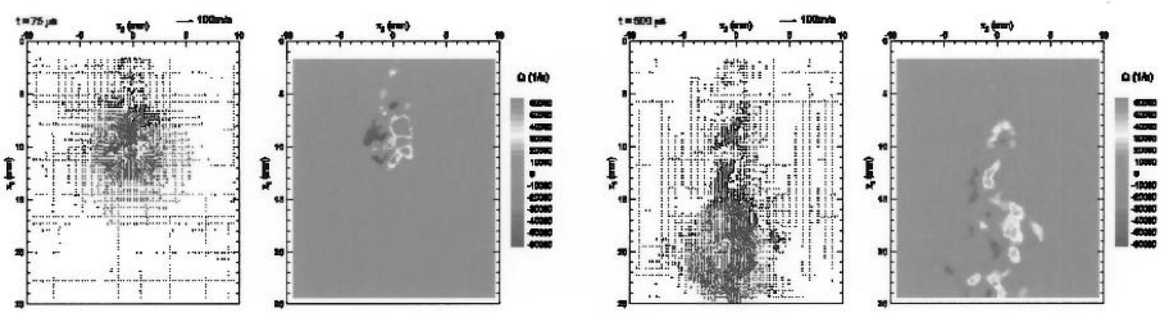

Figure 5: Sample micro-PIV results: resolved velocity fields (left) and out-of-plane vorticity (right).

Impulse Bit Measurements

A miniaturized thrust stand designed by JHU/APL for micro-Pulsed Plasma Thruster development was used to measure SparkJet impulse bit data. The thrust stand was designed to produce vibrations with amplitudes ranging from 40 to 175 nm (consistent with an interferometer using a 670 nm red laser diode) in response to impulse bits ranging from 2 to 7.5 μN-sec. It was used to gather preliminary impulse bit data for a single SparkJet device powered by a 220 nF capacitor rated at 1000 V. Impulse bit data was collected at five discrete voltages levels ranging from 520 to 900 V. These points correspond to energy deposition levels of 30, 40, 54, 70, and 89 mJ. A sample of this data is shown in Figure 6.

Objectives

Design and optimization of an integrated plasma generation structure (Figure 7) will require an understanding of the fundamental physics and coupling phenomena between the individual components of the array (i.e. nearest neighbors) as well as the array and its immediate flow surroundings.[4] The objectives of the research program are to: (1) Investigate the time-dependent interactions between collocated SparkJet actuators; (2) develop a model of an array of individually programmable SparkJet actuators and investigate the ability to phase the pulsed jets; and (3) finalize an array design optimized for normal force generation.

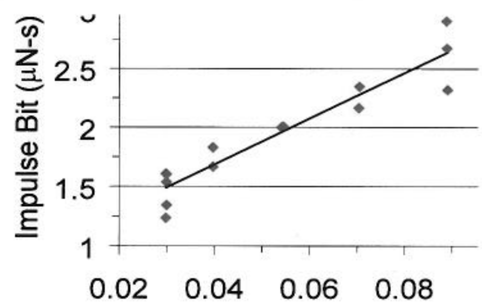

Figure 6: SparkJet impulse bit data.

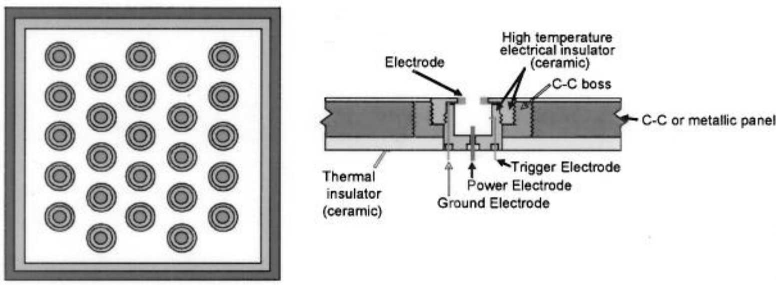

Figure 7: Integrated plasma device based on array of SparkJets.

Status of Effort (Year 2)

Practical application of the SparkJet technology will require the development of distributed actuator arrays. The diminutive size (120-600 μm) and high discharge velocities (400-500 m/s) of the SparkJet actuator make it very difficult to evaluate demonstration units using non-intrusive measurement techniques. To begin optimizing an array of SparkJet actuators for control of high-speed flow, a 3D high-fidelity computational model is required that can represent the small scale effects from the actuators on the large scale phenomenon such as turbulence, transition, fuel mixing and flow separation.[5]

Capturing both small and large effects in one simulation is computational expensive and an alternative method is required.[6] In order to simplify the application-driven simulations of a SparkJet array, the SparkJet device will be modeled as a boundary condition representative of the flow exiting the SparkJet orifice. To this end, modeling of a single device is underway to develop this boundary condition. Current Computational Fluid Dynamics (CFD) models are able to capture the quantitative features, parametric trends, and the qualitative plume shape in a quiescent flow. Figure 8 shows a sample of the SparkJet plume at various time steps consisting of a supersonic core surrounded by low speed entrained flow. Analogous experimental results are required for CFD validation.

Under the subject grant, Year 2 efforts focused on experiments and acquiring high quality data intended for CFD validation, namely the acquisition of plume velocimetry and temperature data.[7]

Figure 8: Sample CFD images of a single SparkJet plume in quiescent flow.

Two techniques were used to characterize the SparkJet flow: high-resolution PIV and digital speckle tomography (DST). The PIV images are higher quality than our previous efforts through the use of a faster camera, smaller interrogation window and a new flow visualization chamber. The DST technique, new to this application, is a non-intrusive quantitative flow visualization technique used to evaluate flows with high density or temperature gradients. The flow visualization images acquired consist of 2D velocity fields and temperature profiles from PIV and DST measurements, respectively.

PIV velocity magnitude images of the SparkJet plume (Figure 9) were obtained via six separate pulses captured at the specified times after energy deposition: 25, 50, 75, 100, 150 and 200 μs. The images capture the entrained flow and qualitatively compare very well with CFD results. In addition, the experimental trends agree well with previous CFD parametric studies.[8] Specifically, the experimental results support the expected shorter plume duration due to reduced viscous effects associated with a larger orifice.

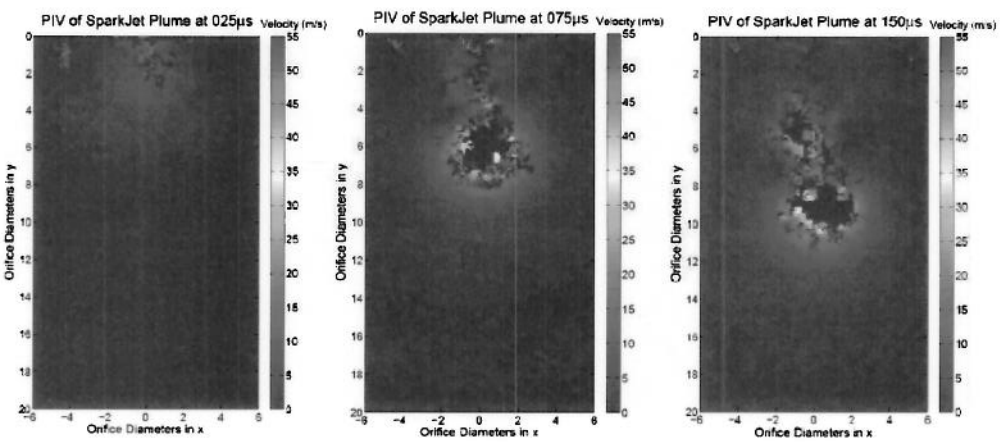

Figure 9: Sample PIV velocity magnitude images of the SparkJet plume.

The temperature profiles obtained from the DST measurements, measured 1.85 mm away from the orifice, show that the temperature of the plume reaches a maximum value of 1600 K at 75 μs. Between 75 μs and 100 μs, there is a sharp decrease in temperature. The sudden drop in temperature across the measurement plane between 75 μs and 100 μs indicates that the majority of hot air generated inside the cavity has moved past the orifice and the plume is no longer sustained by hot expanding air. After 100 μs, there is a more gradual decrease in temperature as seen in Figure 10. These results qualitatively agree well with current CFD predictions.

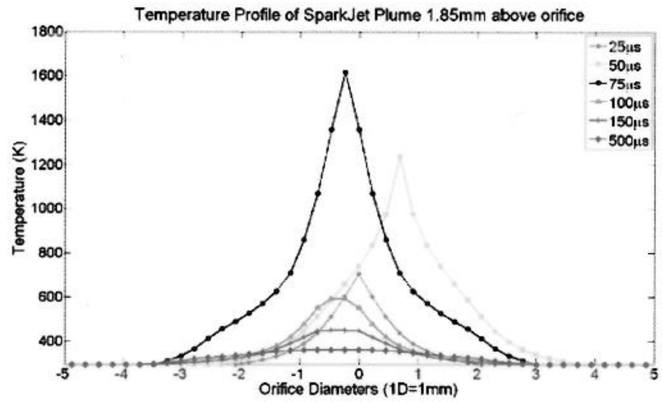

Figure 10. Temperature Profiles of the SparkJet plume 1.85 mm from orifice.

For targeted high-speed applications, the SparkJet electrode and circuit designs have been improved to handle high-energy and high-frequency use. To prevent electrode degradation with each pulse, the electrodes have been changed from Copper to Tungsten (Figure 11). For higher energy deposition levels and, therefore, a stronger pulse, a new circuit board has been designed with increased capacitance and the ability to handle a high frequency power supply.

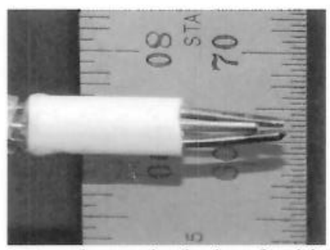

Figure 11: New Tungsten electrode design for high-speed applications.

Target Applications

A number of potential applications for the SparkJet actuator technology are being considered. One such area involves control of flow oscillations in cavities due to resonance induced by flow-acoustic coupling. A cavity flow insert with a row of imbedded SparkJet actuators (Figure 12) is currently being designed by JHU/APL for testing by Dr. Farrukh Alvi and his team at the Advanced Aero Propulsion Laboratory, Florida State University (FSU). Similarly, the control of flow separation in external flows (flows over airfoils and lifting bodies) as well as internal flows (engine inlets and S-ducts) are also areas of active research. Other potential applications include rotating turbomachinery, and supersonic mixing and combustion enhancement. JHU/APL will continue to discuss evolving SparkJet applications with the Air Force and will narrow the application focus as the distributed array technology matures. Since computational results indicate that the device has the potential to penetrate supersonic boundary layers, high-speed applications may be of most interest.

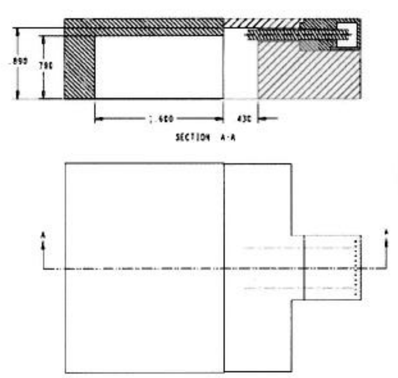

Figure 12: Cavity flow insert for FSU supersonic wind tunnel testing.

Acknowledgment/Disclaimer
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Personnel Supported During Duration of Grant

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Publications

Cybyk, B., Wilkerson, J., Simon, D., "Enabling High-Fidelity Modeling of a High-Speed Flow Control Actuator Array," AIAA-06-8034, 14th AIAA/AHI Space Planes and Hypersonic Systems and Technologies Conference, Canberra, Australia, November 2006.

Taylor, T. and Cybyk, B., "High-Fidelity Modeling of Micro-Scale Flow-Control Devices with Applications to the Macro-Scale Environment," AIAA-2008-2608, 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, Ohio, April 2008.

Haack, S., Land, B., Cybyk, B., Ko, H., Katz, J., "Characterization of a High-Speed Flow Control Actuator Using Digital Speckle Tomography and PIV," AIAA-2008-3759, 4th AIAA Flow Control Conference, Seattle, Washington, June 2008.

SparkJet Actuators for Controlling Flows, Defense Tech Brief, December 2008.

Honors & Awards Received: None in 2008.

AFRL Points of Contact (Year 2)

Drs. Stephen Puterbaugh and Todd Bailie, AFRL/RZTF, WPAFB, OH. Phone: 937-255-7313. Discussed status of compressor research facility move and future SparkJet testing opportunities, June 2008.

Dr. Campbell Carter, AFRL/RZ, WPAFB, OH. Phone: 937-255-7203. Discussion at AFOSR FC&A Portfolio Review, August 2008.

Dr. Todd Bailie, AFRL/RZTF, WPAFB, OH. Phone: 937-255-7313. Discussed opportunity to involve AFIT student in the technology development, submitted informal proposal to Col. Decker at AFIT, September 2008.

Drs. Todd Bailie and William Copenhaver, AFRL/RZT, WPAFB, OH. Phone: 937-255-7313. Discussed possibility of engaging co-op student next summer, November 2008.

Transitions: None in 2008.

New Discoveries:

Provisional Patent Application, 2554-0163, *Unsteady Supersonic Flow Control Device*, January 2008.

Patent Application, 2219-0095, *Solid State Supersonic Flow Actuator and Method of Use*, September 2008.

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